Underwater Glider Networks for Adaptive Ocean Sampling

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LONG-TERM GOALS

The long-term goal of this research is to enable a cooperating group of underwater gliders to perform efficiently and robustly as an autonomous, adaptive sampling network in a three-dimensional, dynamic ocean environment. This will involve developing the mathematical infrastructure and design tools for effecting feedback-controlled, schooling-like network behavior in an unsteady flow field while exploiting the natural dynamics of the ocean.

OBJECTIVES

We are interested in developing the mathematical framework and the integrated design methodology for coordinating a glider network to provide improved sampling efficiency and efficacy using ocean model prediction data, observations and Lagrangian structure computations. The fleet of gliders serves as a mobile and re-configurable sensor network for investigating the ocean. Our technical objectives include the following:

1. To develop glider network control strategies that exhibit “emergent intelligence” at the group level using simple control laws at the individual level, much like schools of fish. Group-level behaviors may include the ability to maneuver in a particular formation, adjust the group shape, size, orientation and density in response to measured (or predicted) data in real time, climb gradients and track and map features.

2. To investigate using the method of controlled Lagrangians as a framework in which network control strategies can be derived from artificial potentials and gyroscopic forces and can be integrated with a graph theoretic setting for describing a time-varying communication topology.

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14. ABSTRACT

The long-term goal of this research is to enable a cooperating group of underwater gliders to perform efficiently and robustly as an autonomous, adaptive sampling network in a three-dimensional, dynamic ocean environment. This will involve developing the mathematical infrastructure and design tools for effecting feedback-controlled, schooling-like network behavior in an unsteady flow field while exploiting the natural dynamics of the ocean.

15. SUBJECT TERMS

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3. To investigate the use of dynamical system theory tools and software for computing Lagrangian structures to understand the dynamics and control of underwater gliders in a three-dimensional ocean environment.

4. To extend the glider network control strategies so that they not only perform successfully in spite of a dynamic ocean environment but also perform well because they exploit knowledge of the dynamics of the sea and the consequential tendencies of the gliders to move easily in certain directions. In particular, the objective is to integrate the network control strategies with the computation and analysis of Lagrangian structures.

5. To develop variational integrators for the simulation of one or more underwater vehicles and investigate the interaction of vehicles and also the interaction with vortex structures.

6. To apply these technologies to adaptive sampling in the AOSN-II Monterey Bay Predictive Skills Experiment in the summer of 2003. This will involve integration with ocean model predictive capabilities and practical glider operating conditions.

APPROACH

The approach and methodologies employed, corresponding to the above objectives, are as follows:

1. We will build on the technique of adaptive gradient climbing and maneuvering (see Leonard and Fiorelli [2001], Ogren, Fiorelli and Leonard [2002], Bachmayer and Leonard [2002]), whereby the group, serving as a re-configurable sensor array, uses its local information and virtual leaders to locate interesting regions and to adapt accordingly. The vehicles respond according to feedback control laws derived from artificial potentials and stay near virtual leaders that are driven by measurements of the environment, for example, gradient measurements.

2. The use of controlled Lagrangians has already been successful in the control of single systems (see, for example, Chang et al. [2002]). An important next step is to develop this theory in a network context (with the individual systems connected by sensor and information flow) and ultimately to merge it with the other techniques for a glider network, as in item 1. This effort will require models for gliders, such as those developed by Leonard and Graver [2001].

3. Much progress has been made, using the software MANGEN, on the problem of understanding flow structures in Monterey Bay and other ocean and coastal environments. We are in the process of merging this work with glider dynamics so that we can determine the effect of the dynamics on the vehicles and how to respond appropriately.

4. Our initial strategy is to navigate, using groups of vehicles moving together in a coordinated way as a result of potential and gyroscopic control strategies, along *navigation channels* (that is, stable manifolds, or more precisely, repelling material lines) in the sense of the finite-time, computational theory (see, for instance, Haller and Yuan [2002]) in order to reach the *front surfaces* (that is, unstable manifolds, or more precisely, attracting material lines). George Haller of MIT is a consultant and collaborator.

5. We plan to use existing variational methodologies, such as those in Rowley and Marsden [2002] and references therein as simulation tools; these methods show superior performance in terms of energy behavior, especially for long-time or complex simulations (see, for instance, Lew et al [2002]). We aim to also make use of known variational structures in fluid mechanics, especially those involving

the interaction of solids and fluids (e.g., Leonard and Marsden [1997]) and the interaction of vortex structures and solids (e.g., Shashikanth et al [2002]).

6. To contribute to the adaptive ocean sampling experiment in Monterey Bay in the summer of 2003, we will integrate our methods with the tools of the collaborating research teams so that we can demonstrate some of the versatility and capability of an underwater glider fleet serving as a sensor network. The output from the ocean models, namely the predicted data and the determination of areas of greatest model uncertainty and scientific interest, will provide the input to our glider network motion planning and feedback control strategy. Feeding back model prediction data and if possible observational data, the strategy will address both the problem of getting the glider network to the features/sites of interest and the problem of guiding the glider network so that it most effectively samples the features/sites of interest once it is there. We have already begun coordination with the Harvard team to link the HOPS model with control strategies and with the experimental team of Dave Fratantoni at WHOI to implement control laws on the underwater vehicles, first in Buzzard's Bay and then in Monterey Bay. We are building a simulator to use the model predicted data to test various control strategies we have developed, including gradient climbing and virtual leader methods, and also to test the effect of the currents using the MANGEN software which identifies coherent Lagrangian structures.

The effort is led by N. Leonard (PI) with the Caltech contribution led by J. Marsden (co-PI). C. Rowley (co-PI) focuses on low-dimensional modeling of fluids and R. Bachmayer (research staff at Princeton) focuses on simulation and implementation issues. Graduate students E. Fiorelli and P. Bhatta (Princeton) and S. Shadden (Caltech) focus on the coordinated control strategies and the integration with Lagrangian structure computations. C. Coulliette (post-doc at Caltech) and Francois Lekien (graduate student at Caltech) focus on computing and exploiting Lagrangian structures from flow data.

WORK COMPLETED

This effort started late in FY002. Therefore, while several of the objectives discussed above have been initiated, none of the proposed work items is fully completed yet.

RESULTS

Some preliminary results show that:

1. The effect of the (time-dependent) currents in Monterey Bay on the underwater vehicles planned for use in the summer 2003 experiment is considerable and must be taken into account. In addition, simple simulation examples show that the currents can also be exploited; in particular, the coherent Lagrangian structures identified by MANGEN play a key role.

2. It is possible to navigate along interesting flow structures in Monterey Bay using the techniques of virtual leaders and gradient climbing, as shown in Figure 1.

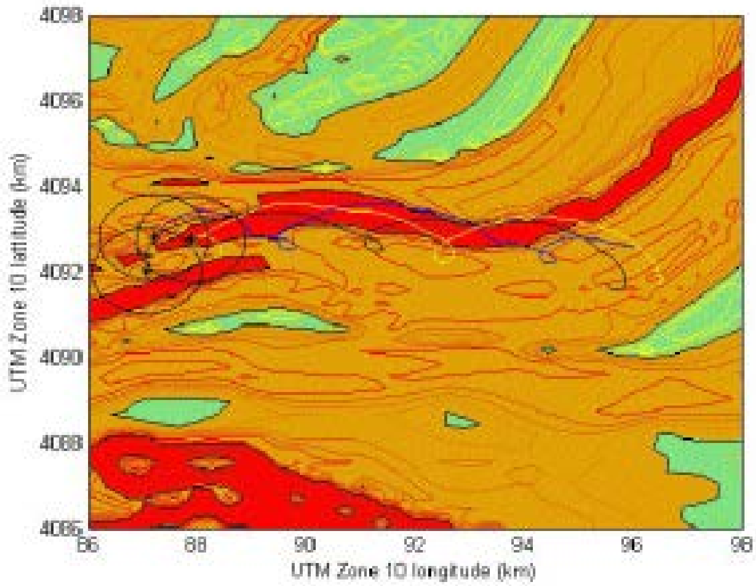

Figure 1: Paths of three vehicles in a sampling network traversing a ridge of interest.

3. An improvement of data gathering and front tracking capability can be achieved (in a preliminary simulation environment) by using strategies involving groups of vehicles.

4. An examination of some MANGEN two-dimensional simulations based on HF Radar Data suggests that stable material lines correspond to temperature fronts in Monterey Bay. Figure 2 shows the superposition of the velocity field and the temperature field and from this one can see a correlation between these two. This figure provides motivation for us, in the future, to explore the conjecture that fronts, such as temperature fronts, relate to attracting material lines.

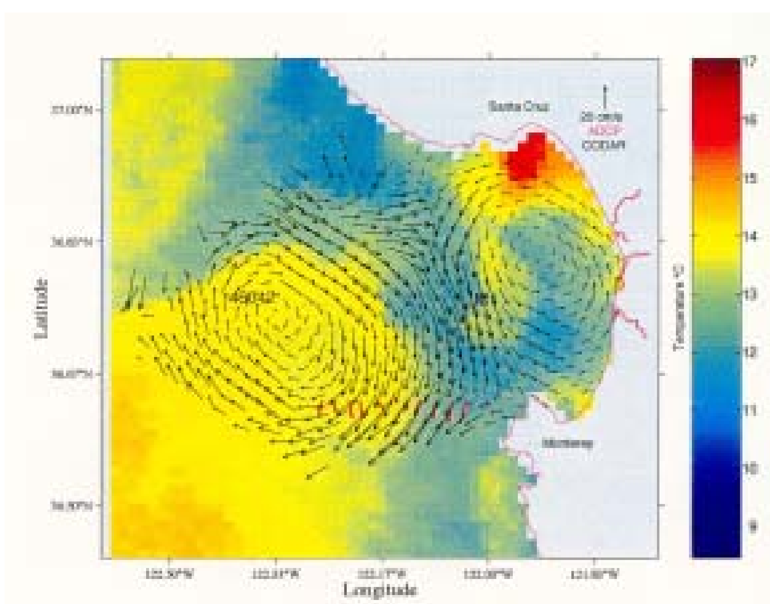

Figure 2: Superposition of flow field on temperature field indicates coincidence of Lagrangian structures with fronts.

IMPACT/APPLICATIONS

The infrastructure we are developing will lead to the understanding of and design of specific control strategies for underwater glider networks in a dynamic ocean environment. This impacts not only the gathering of data for the adaptive ocean sampling experiment to be performed next summer in Monterey Bay, but most importantly the longer term plans for finding and tracking features of interest and gathering data all in a systematic and sustainable way in various regions of Earth's oceans.

TRANSITIONS

This effort started late in FY002 and so none of the planned transitions (for example, to the other AOSN-II teams) are completed yet.

RELATED PROJECTS

Leonard participates in an NSF/KDI funded project joint with A.S. Morse (Yale), P. Belhumeur (Columbia), R. Brockett (Harvard), D. Grunbaum and J. Parrish (U. Washington) on coordination of natural and man-made groups. Schooling of fish and "schooling" of autonomous underwater vehicles are studied. A multiple-vehicle experimental test-bed is being developed at Princeton. See http://graham.princeton.edu/~auvlab/ and http://www.eng.yale.edu/grouper/

Leonard participates in an AFOSR funded project on Coordinated Control of Groups of Vehicles. This is a joint project with V. Kumar and J. Ostrowski at University of Pennsylvania. A focus of the project is understanding cooperation in the context of coordinated control of distributed, autonomous agents, and the collection and fusion of the sensor information that they retrieve.

With colleague E. Belbruno, Leonard has worked on a project for Global Aerospace Corporation (funded by NASA) on low-energy trajectory control of a stratospheric balloon network. The objective is to manage the geometry of the constellation of (actuated) balloons for science and communication applications in the presence of a non-uniform flow field at 35 km altitude much like the problem of coordination of groups of underwater gliders in a non-uniform flow field.

Leonard and Marsden work on control and stabilization of mechanical systems, including autonomous underwater vehicles with internal actuation (e.g., internal rotors) using the method of controlled Lagrangians. This is a joint project with A.M. Bloch (U. Michigan), D.E. Chang (UCSB) and C.Woolsey (Virginia Tech).

Marsden is involved in an NSF/ITR project at Caltech on *Multiscale modeling and simulation* that aims to improve both the mathematical models and the simulation of multiscale phenomena, including fluid dynamical simulations and the variational integrator methodology. That project will interact with the present one in the simulation and modeling aspects of the problem.

Marsden is also working with Chad Couliette (who is the PI) on the ONR project *Lagrangian Analysis and Forecasting in the Oceans and Coastal Zones*. This project uses dynamical systems techniques to develop a detailed understanding of transport and mixing in the oceans and coastal zones. Ultimately, the program will lead to Lagrangian forecasting—the ability to make specific deterministic predictions about the advection and diffusion of passive scalars in the ocean. That project developed the software MANGEN which will be quite useful in the context of the current proposal. The project also developed the Open-boundary Modal Analysis (OMA) which is a substantial improvement on current techniques for data interpolation (to avoid dead zones, for example). These techniques may be quite useful, especially in the long run, in the problem of incomplete data sets in, for example, Monterey Bay.

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PUBLICATIONS

This effort started late in FY002, and so no papers funded by this project have appeared yet.